

Chapter 1

Isoscalar and isovector neutron-proton pairing

A. V. Afanasjev

*Department of Physics and Astronomy, Mississippi State University,
MS 39762, USA,
afanasjev@erc.msstate.edu*

*Joint Institute for Heavy-Ion Research, Oak Ridge,
TN 37831, USA*

Neutron-proton (np –) pairing is expected to play an important role in the $N \approx Z$ nuclei. In general, it can have isovector and isoscalar character. The existence of isovector np –pairing is well established. On the contrary, it is still debated whether there is an isoscalar np –pairing. The review of the situation with these two types of pairing with special emphasis on the isoscalar one is presented. It is concluded that there are no substantial evidences for the existence of isoscalar np –pairing.

1. Introduction

The invent of new generation of detector facilities (such as GAMMAS-PHERE and EUROBALL) and radioactive beams in the 90ies of last century has opened up new avenues to study the nature of nuclear interactions, in particular, np –pairing at the $N = Z$ line. This also stimulated theoretical studies of this type of pairing.

The existence of the np –pairing crucially depends upon the overlap between the neutron and proton wave functions.^a Protons and neutrons occupy the same orbitals in $N = Z$ nuclei and this leads to an increased neutron-proton pair correlations which under specific circumstances can

^aIt is frequently stated that near degeneracy of the proton and neutron Fermi surfaces favors the development of neutron-proton pairing. This is, however, not true considering that Coulomb interaction creates an energy gap of approximately 7 MeV between the proton and neutron states of the same structure (and respective Fermi surfaces). This fact is ignored in a number of publications.

form np -pair condensate. A suppression of this type of pairing is expected if the system is driven out of the isospin-symmetric state. Thus, np -pairing is expected only at $N = Z$ line or in its close vicinity.^{1,2} Indeed, it is well known that in the nuclei away from the $N = Z$ line proton-proton (pp) and neutron-neutron (nn) pairing dominate and there are no signs of np -pairing. The mechanism driving this suppression is encountered not only in nuclei but also in other many-fermionic systems (such as superconductors and superfluids) where the particles lie on two different Fermi surfaces (see Ref.³ for more details).

These np -correlations can be isoscalar and isovector. Figuring out whether they form a static pair condensate/pairing (an average field) in respective channel has been a challenge since medium mass $N = Z$ nuclei have come into reach of experiment. In this manuscript, I review the situation with the current understanding of isoscalar and isovector np -pairing. A specific attention is paid to isoscalar np -pairing since it is not clear at present whether this type of pairing exists or not. The general consideration of the np -pairing is presented in Sect. 2. The impact of the np -pairing on different physical observables and processes in non-rotating and rotating nuclei is discussed in Sects. 3 and 4, respectively.

2. Neutron-proton pairing: general considerations

Isotopic invariance of nucleon-nucleon interaction tells us that the nuclear components of the interaction in the systems proton-proton, neutron-neutron and neutron-proton are very similar. A nucleon with isospin quantum number $\tau = 1/2$ may be in one of two states, $\tau_z = -1/2$ (proton) and $\tau_z = +1/2$ (neutron). Nuclear many-body states are labeled with isospin quantum number T , whose third component is its projection $T_z = (N - Z)/2$ (N and Z are neutron and proton numbers of the nucleus, respectively).

Let me consider a pair of two nucleons. For such a system, two distinct isospin states with $T = 1$ and $T = 0$ can be defined. The spin projections $T_z = -1, 0, 1$ are possible for a $T = 1$ nucleon-nucleon system. Here $T_z = -1$ corresponds to a proton-proton system, $T_z = 1$ to a neutron-neutron system, and $T_z = 0$ to a neutron-proton system. The nucleons in the $T = 1$ system have total spin $J = 0$ in order to ensure antisymmetry of the total nucleon-nucleon wave function. For the same reasons, $T = 0$ proton-neutron systems can have only $T_z = 0$; the situation with total spin is discussed below.

The scattering of the nucleon pairs with given quantum numbers of isospin t^b and angular momentum J is responsible for different kinds of pairing correlations.^{4,5} The pair potential Δ_{Jt} is also defined by the spin and angular momentum of pair. It is well known that in even-even nuclei isovector $t = 1$ like-particle pairing is responsible for the spins and parities ($J^\pi = 0^+$) of the ground states and for appreciable separation in energy of ground and excited states. For this pairing, a nucleon pair couples to angular momentum $J = 0$.

The situation is different for neutron-proton pairing. There are two possible types of pairing: isovector one with $t = 1$ and $J = 0$ and isoscalar one with $t = 0$. It is frequently stated that in the case of isoscalar pairing the dominant components of pair potential correspond to either $J = 1$, or $J = J_{max} = 2j$, where j is the nucleon angular momentum. However, the results of the calculations of Ref.⁶ presented in Fig. 1 show that this is not always a case. Indeed, at spin $I = 0$ in the $t = 0$ pair band of ^{80}Zr there is no $J = 1$ or $J = 3$ pairs. The pair potential is dominated by the $J = 5$ pairs and $J_{max} = 2j = 9$ pair comes only as a second in importance.

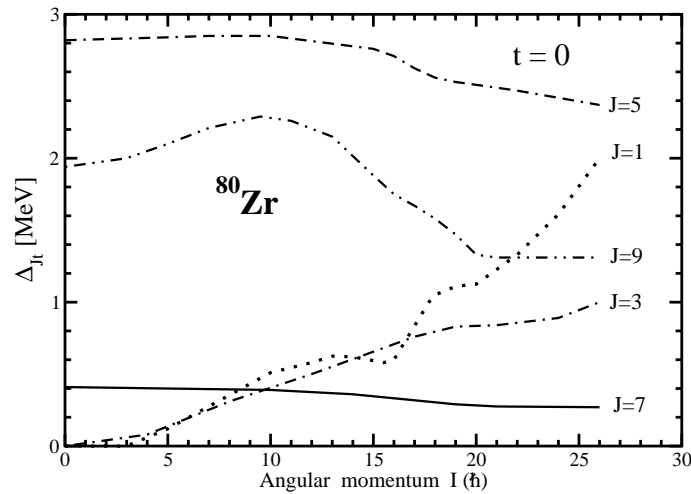


Fig. 1. Angular momentum components of the pair potential $\Delta_{J,t=0}$ for the $t = 0$ pair band in ^{80}Zr . Based on the results presented in Fig. 9 of Ref.⁶

Earlier calculations have pointed on the exclusiveness of the $t = 0$ and

^bThe lower-case letter t is used for the isospin of the pair-field in order to avoid the confusion with the total isospin of the states denoted by T .

$t = 1$ np -pairing phases.^{7,8} However, more recent calculations show that $t = 0$ and $t = 1$ pairing phases can coexist. This was shown in Ref.⁹ within the isospin generalized BCS and HFB frameworks based on the G-matrix interaction. Ref.¹⁰ illustrated that the sudden phase transition between the $t = 0$ and $t = 1$ pairing modes becomes smeared out in number-projected Lipkin-Nogami (LN) calculations.

When considering np -pairing it is important to remember the basic difference between shell model and mean field (MF)/density functional (DFT) models since the neglect of this difference frequently leads to confusions and contradictions. The shell model Hamiltonian is usually written in the particle-particle representation. Thus, in the shell model there is no distinct division into pairing- and single-particle (mean) fields. On the contrary, the configuration space of the MF and DFT models is separated into particle-hole (mean field) and particle-particle (pairing field) channels. As a consequence, the shell model definition of pairing in terms of $L = 0, S = 1, T = 1$ and $L = 0, S = 1, T = 0$ pairs is completely inappropriate from the point of MF/DFT models (see discussion in Ref.¹⁰ and references therein). This means that the existence of isoscalar and isovector np -pair correlations in spherical shell model is not equivalent to the existence of isoscalar and isovector np -pairing [pair condensate] in the MF/DFT frameworks. As a consequence, I only consider here the results obtained in the MF/DFT frameworks.

2.1. *Isovector neutron-proton pairing*

At present, the situation with the isovector np -pairing is most clarified. The isovector np -pairing is absolutely necessary in order to restore the isospin symmetry of the total wave function.¹¹ Its strength is well defined by the isospin symmetry. A number of experimental observables such as binding energies of the $T = 0$ and $T = 1$ states in even-even and odd-odd $N = Z$ nuclei,¹²⁻¹⁴ the observation of only one even-spin $T = 0$ band in ^{74}Rb ¹⁴ instead of two nearly degenerate bands expected in the case of no $t = 1$ np -pairing *clearly point on the existence of pair condensate in this channel*. The analysis of pairing vibrations around ^{56}Ni indicates a collective behavior of the isovector pairing vibrations but does not support any appreciable collectivity in the isoscalar channel.^{15,16} The detailed discussion of binding energies of the $T = 0$ and $T = 1$ states in even-even and odd-odd $N = Z$ nuclei as well as pairing vibrations around ^{56}Ni is given in the contribution of A. Macchiavelli in this Volume.¹⁷

2.2. Isoscalar neutron-proton pairing

While the situation with isovector np -pairing is settled, the one with isoscalar np -pairing is full of controversies. These controversies are generally related to the microscopic origin of isoscalar np -pairing and whether the isoscalar np -pair correlations lead to a pair condensate.

The calculations with the realistic (bare) forces (Paris force, Argonne V14 force) indicate that the isoscalar pairing gap in the symmetric nuclear matter is 3 times larger than the isovector one.¹⁸ In finite nuclei with $Z = N = 35$, calculated isoscalar pairing gap is of the order of 3 MeV,¹⁸ while the experimental isovector pairing gap is around 1.8 MeV (see Fig. 4 in Ref.¹²). However, despite that no convincing fingerprints of isoscalar np -pairing has been found so far (see discussion below).

The potential problem is due to the transition from realistic to effective interaction: the extremely strong $t = 0$ np -pairing emerges essentially from the fact that with respect to the $t = 1$ channel, dominated by the central force, the tensor force is acting additionally. However, the medium modification (screening) of the tensor force is still controversial subject.²⁰ For example, higher shell admixtures make the tensor force appear weaker in the valence space.¹⁹ In addition, one cannot exclude the possibility that the tensor force is largely screened in the medium, and, thus, the enhancement of the $T=0$ gap values may be brought back closer to the values of the $T = 1$ case.²¹

While the structure of interaction (central force) is the same in isovector pairing channel of the theories based on realistic and effective forces, the addition of tensor component into isoscalar pairing channel of the models based on effective forces may be necessary for a correct description of np -pairing in this channel. In the existing mean-field models, the tensor component of pairing is neglected. Although, some attempts were made to approximate bare tensor interaction by effective density dependent zero-range δ -force,^{18,21} the validity of such an approximation for different physical observables has not been tested in the mean field calculations.

Recent Hartree-Fock-Bogoliubov (HFB) studies²² for finite nuclei with chiral $N^3\text{LO}$ two-nucleon interaction for pairing led to the results which are opposite to the ones discussed above. They showed that this type of nuclear forces favors isovector over isoscalar pairing, except in low- j orbitals. The suppression of isoscalar pairing has been traced to the effects of spin-orbit splitting, the D waves and additional repulsive 1P_1 channel. Note that the role of spin-orbit field in the suppression of isoscalar pairing has also been

discussed in Refs.^{23,24}

The presence or absence of isoscalar np -pair condensate sensitively depends on the strength of the pairing in this channel (see Sect. 3.1 below). At present, it is obvious that microscopic theories give no clear guidance on what strength has to be used for isoscalar np -pairing in the MF/DFT models. It was suggested to extract the strengths of the $t = 0$ np -pairing from experimental Wigner energies (see Sect. 3.1 below). However, there are alternative explanations of the Wigner energy which do not involve $t = 0$ np -pairing. As a consequence, on the MF/DFT level there is no generally accepted procedure on how to extract the strength of isoscalar np -pairing. This situation is clearly unsatisfactory. Thus, the systematic comparison between theory and experiment with the goal to find the evidences for isoscalar np -pairing and physical observables sensitive to it becomes imperative. Such a comparison is presented below.

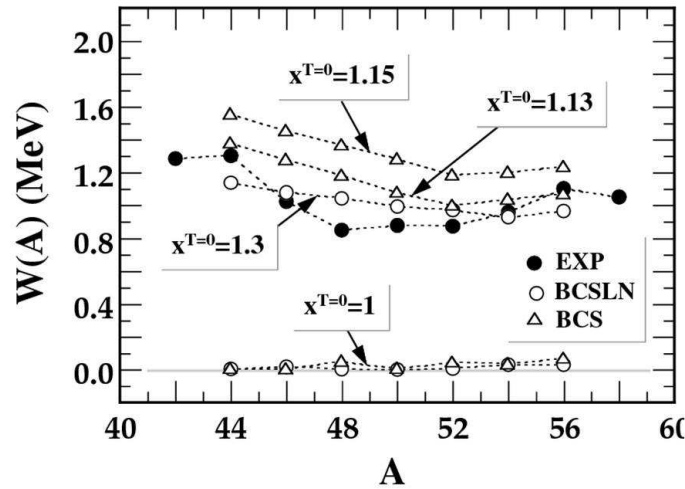


Fig. 2. Experimental and calculated strength $W(A)$ of the Wigner energy for pf -shell nuclei. The results of calculations for different values of $x_0^{t=0}$ and different models are shown. From Ref.¹⁰ Note that the authors of this reference use capital letter T for the isospin of the pair-field, while lower-case t is used for it in the current manuscript.

3. Neutron-proton pairing at no rotation

3.1. Wigner energy

It is well known that a term proportional to isospin T has to be included into nuclear mass formulae in order to reproduce the isospin dependence of masses.²⁵ This term called Wigner energy has a form $E_W = W(A)|N - Z|/A$ in which $W(A)$ stands for mass-dependent strength. It gives rise to a cusp at $N = Z$ in the curves of masses along an isobaric chain. The physical origin of this energy has not definitely been established until now and it still remains the subject of the debate (see Sect. II in Ref.²⁶ for a recent review). The modern mean field models or DFT do not explain it; this term is added as an ad-hoc phenomenological term.

As suggested in Ref.² one of possible microscopic explanations of this term involves the isoscalar $t = 0$ np -pairing. The experimental Wigner energies can be reproduced in this scenario (Ref.¹⁰) but this requires the strength of isoscalar ($G_{np}^{t=0}$) np -pairing which is larger than the one of isovector ($G_{np}^{t=1}$) np -pairing. No isoscalar np -pair condensate is formed for the case $G_{np}^{t=0} = G_{np}^{t=1}$ (see Fig. 2). One then can define the scaling factor $x_0^{t=0} = G_{np}^{t=0}/G_{np}^{t=1}$. The fit to experimental Wigner energies gives the $x_0^{t=0}$ values of ~ 1.13 and ~ 1.30 for BCS and BCSLN models in the fp shell (see Fig. 2) and ~ 1.25 in the BCSLN model in the $A \sim 76$ mass region. These high values of $x_0^{t=0}$ lead to a visible impact of the $t = 0$ np -pairing on the rotational properties of the $N \approx Z$ nuclei at high spin.^{2,10} However, their detailed analysis discussed in Sect. 4 does not support the presence of isoscalar np -pairing.

Alternative explanations of the Wigner energy which do not involve isoscalar np -pairing have been proposed in Refs.²⁷⁻²⁹ It was suggested in Refs.^{27,28} that the RPA correlation energy should be taken into account in order to describe experimental masses in the vicinity of the $N \approx Z$ line. In this formalism, the Wigner energy results from the collectivity of the isorotation, which itself is the result of the isorotational noninvariance of the isovector pair field. In another scenario,²⁹ the combination of an isorotational invariant effective interaction in the particle-hole channel with isovector pairing interaction gives the Wigner energy, provided the pairing correlations are treated beyond mean field approximation and isospin is conserved.

One should note, however, that all of these results have to be taken with a grain of salt because they are probably crude approximations to the

real situation due to employed simplifications. For example, Refs.¹⁰ ignore the conservation of isospin and correlations beyond mean field, whereas the results of Refs.^{27,28} were obtained in schematic model.

3.2. Binding energies of the $T = 0$ and $T = 1$ states in even-even and odd-odd $N = Z$ nuclei

The analysis of experimental binding energies of the $T = 0$ and $T = 1$ states in even-even and odd-odd $N = Z$ nuclei^{12–14} clearly points on the existence of pair condensate in the isovector channel but provides no evidence for an isoscalar pair condensate in such nuclei. The detailed discussion of this topic is given in the contribution of A. Macchiavelli in this Volume.¹⁷ The observed spectra of adjacent even-even and odd-odd nuclei $N = Z$ nuclei are distinctly different. This also allows to exclude pure $t = 0$ np -pairing field with Δ larger than the single-particle level distance.³⁰

3.3. Neutron-proton pairing in transfer reactions

The collectivity of np -pairing correlations can be accessed by means of pair transfer from the $T = 1(0)$ ground state of the $A + 2$ ($N = Z$) nucleus to the ground state of the A ($N = Z$) nucleus. The analysis of the influence of the np -pairing on np -pair transfer in $N = Z$ nuclei within a single- j shell model space with allowance for both $t = 0$ and $t = 1$ pairing interactions^{31,32} lead to the conclusion that np -pairing can enhance the cross-section by a factor 3 as compared to conventional shell-model calculations. However, more sophisticated analysis³³ pointed out that the fundamental difference in the structure between the $t = 0$ vacua in even-even and odd-odd nuclei results in a quenching of the $T = 0$ pair transfer even in the presence of strong $t = 0$ np -pairing. So far experimental measurements of the np -pair transfers in the $N = Z$ nuclei have not provided conclusive answer on whether the $t = 0$ np -pair condensate is formed.¹⁷

3.4. Pairing vibrations

Near closed shells, the strength of the pairing force relative to the single-particle level spacing is expected to be less than the critical value needed to obtain a superconducting solution, and the pairing field then gives rise to a collective phonon.¹⁵ It then seems natural to ask whether $t = 0$ collective effects may show up as a vibrational phonon? A detailed analysis of isovector pairing vibrations around ^{56}Ni presented in Refs.^{15,16} confirms

their collectivity. On the contrary, the analysis of the excitation spectrum around this nucleus indicates only a single-particle character for the isoscalar channel.¹⁶

4. Neutron-proton pairing in rotating nuclei

The properties of the $N \approx Z$ rotating nuclei were in the focus of the debate on the existence of isoscalar and isovector np -pairing. The following physical observables

- the size of the moments of inertia,^{2,6,10}
- the frequencies at which the pairs of particles align their angular momentum (band crossing frequencies^{c6,10,11,34-37}),
- deformation properties,⁴⁰
- unexpected mixing of configurations,⁴¹⁻⁴³
- the properties of terminating states^{40,44}

have been discussed in the literature as possible indicators of the np -pairing in rotating $N \approx Z$ nuclei.

As discussed in Sect. 2.1 the evidences for the existence of isovector np -pairing are very strong. The investigation of rotational structures, namely, the observation of only one even-spin $T = 0$ band in $^{74}\text{Rb}^{14}$ instead of two nearly degenerate bands expected in the case of no $t = 1$ np -pairing supports the existence of pair condensate in this channel.

On the other hand, no such strong arguments exist for isoscalar np -pairing. Thus, it was suggested in Ref.⁴³ to investigate rotating $N \approx Z$ systems within the isovector mean-field theory¹¹ with the goal to see whether the discrepancies between this theory and experiment can be related to $t = 0$ np -pairing. This theory assumes that there is no isoscalar np -pairing, but takes into account isovector np -pairing and isospin symmetry conservation. A clear advantage of this theory is the fact that standard mean field models with only $t = 1$ like-particle pairing can be employed. The basis modification of these theories lies in adding the isorotational energy term $T(T+1)/2\mathcal{J}_{iso}$ to the total energy. Since, however, all low-lying rotational bands in even-even $N = Z$ nuclei have isospin $T = 0$, this term vanishes. On the level of accuracy of the standard mean-field calculations, the restoration of the isospin symmetry (which takes care of the $t=1$ np pair field) changes only the energy of the $T = 1$ states relative to

^cNote that different authors attribute the shift of crossing frequency in rotational bands either to isovector^{11,34,35} or isoscalar³⁵⁻³⁷ np -pairing or their combination.^{2,6,10}

the $T = 0$ states.¹¹ With this in mind, the rotating properties were studied by means of the cranked Relativistic Hartree-Bogoliubov⁴⁵ (CRHB) theory.

At high spin, the impact of $t = 1$ pairing is negligible and consequently it can be neglected. In such situation, the isospin broken at low spin by isovector pairing is conserved automatically.⁹ Thus, the high spin ($I \geq 15\hbar$) states were systematically studied by the cranked Relativistic Mean Field (CRMF)⁴⁶ approach which assumes zero pairing^d. In the calculations without pairing, the shorthand notation $[p, n]$ indicating the number $p(n)$ of occupied $g_{9/2}$ proton (neutron) orbitals is used for labeling of the configurations.

4.1. Moments of inertia

Since $t = 0$ pairs carry angular momentum, a $t = 0$ np -pair field is expected to increase the moments of inertia.^{2,6,10} In contrast to the *static* $t = 1$ pair field, which is suppressed by the Coriolis anti-pairing (CAP) effect, *static* $t = 0$ np -pairing is favored by rotation. The suggested microscopic mechanism behind that is the following.² The rotation increases the number of pairs of nucleons with parallel coupled angular momenta, thus enforcing the $t = 0$ np -pairing. In this pairing phase, angular momentum is built by the np -pairs smoothly aligning along the rotational axis, without involving any pair breaking mechanism typical for $t = 1$ pairing. Note that $t = 0$ np -pairing saturates with increasing frequency. Thus, at large angular momentum, where the *static* $t = 1$ field is destroyed, a substantial difference between experimental moments of inertia and the ones obtained in the calculations without pairing may indicate the presence of the $t = 0$ np -pair field.

Fig. 3 shows that the moments of inertia of rotational bands in the $N \approx Z$ nuclei are well reproduced by the CRHB calculations before first band crossings. The accuracy is the same as for neighboring $N \neq Z$ nuclei. The CRHB calculations as well as the ones of Ref.¹⁰ indicate that after first proton and neutron paired band crossings the static $t = 1$ pairing correlations are essentially gone. Indeed, above these crossings the moments of inertia obtained in the CRMF and CRHB calculations are very similar. The experimental moments of inertia of the $N \approx Z$ nuclei above band crossings are well reproduced by the unpaired CRMF calculations (as well

^dIn addition, the cranked Nilsson-Strutinsky (CNS) approach⁴⁷ has been used for the study of high spin states. Note that the results of the CNS calculations are similar to the CRMF ones so they are not discussed here.

as cranked Nilsson-Strutinsky calculations⁴³), where it turned out to be important that the response of the nuclear shape to rotation was properly taken into account. *Thus, no systematic underestimate of the moments of inertia, which could be taken as an evidence for a $t = 0$ np -pair field, could be identified.*

4.2. Band crossing frequencies

A delay of the first band crossing in the ground-state band of an even-even $N = Z$ system has been discussed as an evidence for $t = 0$ np -pairing in Refs.^{36,37} HFB³⁷ and cranked shell model³⁶ calculations in the $f_{7/2}$ subshell at fixed deformation indicate that the increase of the value of the $t = 0$ np -pair strength results in a delay of the crossing frequency in the ground-state band of $N = Z$ even-even nuclei.

However, cranked shell model investigations^{11,34,35} at fixed deformation show that such a delay can also be caused by the $t = 1$ np -pairing. On the contrary, more realistic total routhian surface calculations (TRS) with approximate particle number projection by means of the Lipkin-Nogami method show that in the case of superdeformed band in $N = Z$ ⁸⁸Ru nucleus the paired band crossing takes place earlier if the isoscalar np -pairing is present (see Fig. 9 in Ref.¹⁰).

Most of these investigations ignore the isospin conservation^{9,11} and deformation changes⁴³ that are expected to play a crucial role in the $N \sim Z$ nuclei. Consequently, at present there are no reliable theoretical predictions on the magnitude of the shift (if any) of the band crossing frequencies in the $N = Z$ nuclei as compared with the $N \neq Z$ nuclei.

The CRHB calculations within the framework of isovector mean field theory provide rather good description of band crossings in the $N \sim Z$ (see Fig. 3 and detailed discussion in Refs.^{43,57}) which is comparable with the one achieved in the nuclei away from the $N = Z$ line. Similar level of agreement is achieved also in the TRS³⁸ and projected shell model³⁹ calculations without np -pairing. These results substantially weaken the argumentation in favor of the presence of the $t = 0$ np -pairing.

4.3. Deformation properties

It was predicted in Ref.⁴⁰ that the $t = 0$ np -pairing generates an enhancement of the quadrupole deformation in the $N = Z$ nuclei. Fig. 4 compares all available measured transition quadrupole moments Q_t of observed bands

in the $N \approx Z$ $A = 58 - 75$ nuclei with the ones of assigned configurations. These data (both absolute values and relative changes in Q_t with particle number and spin) agree rather well with the results of the CRMF, CRHB and CNS calculations (see Refs.^{43,48-54} for more detailed discussion). One can also see that subsequent additions of $g_{9/2}$ particle(s) increase the transition quadrupole moment both in calculations and experiment. This analysis indicates that *no enhancement of quadrupole deformation in the $N = Z$ nuclei (which is expected in the presence of $t = 0$ np -pairing⁴⁰) is required in order to reproduce experiment within the framework of isovector mean field theory.*

4.4. Unexpected mixing of configurations

In some nuclei, the [2,2] and [3,3] configurations are located very close in energy (see Fig. 14 in Ref.⁴¹ for ^{70}Br , Fig. 10 in Ref.⁴³ for ^{72}Kr and Fig. 6 in Ref.⁴² for ^{73}Kr). If the $t = 0$ np -pairing is present, then these configurations are expected to be mixed. A mixing represents the scattering of a proton and neutron on identical negative parity $N = 3$ orbitals into identical $g_{9/2}$ orbitals, and vice versa. Such pair has an isospin $t = 0$ since the proton and neutron are in the same space-spin state. Although some indications of a mixing in these configurations exist (especially in ^{73}Kr ⁴²), it does not provide a sufficient evidence for the presence of a $t = 0$ pair field (see detailed discussion in Refs.⁴¹⁻⁴³). Rather it may indicate weak dynamical $t = 0$ pair correlations as suggested by the Monte Carlo shell model calculations^{43,55} or just mixing of energetically close configurations by residual interaction.^{42,43}

4.5. Terminating states

It was shown in Refs.^{10,40} that the pair scattering from the $d_{3/2}$ and $f_{7/2}$ orbits into the aligned $g_{7/2}$ and $f_{7/2}$ orbits, which is entirely due to $t = 0$ np -pairing, triggers the onset of collectivity for the states higher than $I = 16^+$ in ^{48}Cr . This can enhance the E2-transition rates between the yrast states with $I \geq 16^+$. This scenario is different from the standard one obtainable, for example, in cranked Nilsson-Strutinsky approach.⁴⁷ However, no experimental data on the states above $I = 16^+$ are available in ^{48}Cr so far.

Theoretical analysis of the energy differences between terminating $f_{7/2}^n$ and $f_{7/2}^{n+1}d_{3/2}^{-1}$ states in the $A \sim 44$ nuclei within the Skyrme DFT showed

that there is a good agreement with experiment for $N > Z$ nuclei and visible discrepancies for the $N = Z$ nuclei.⁴⁴ It was suggested in Ref.⁴⁴ that the deviations from the data for the $N = Z$ nuclei are due to the $t = 0$ np -pairing. However, isospin symmetry restoration is important for DFT description of the $N = Z$ nuclei and its inclusion improves the description of the data.⁵⁶ In addition, the DFT results sensitively depends on the employed parametrization.⁵⁶

5. Conclusions

The physics of isoscalar and isovector neutron-proton pairing has been systematically reviewed in this article. At present, the existence of isovector np -pairing is well established. The isovector np -pairing is absolutely necessary in order to restore the isospin symmetry of the total wave function. Its strength is well defined by the isospin symmetry. A number of experimental observables such as binding energies of the $T = 0$ and $T = 1$ states in even-even and odd-odd $N = Z$ nuclei, the structure of rotational bands in ^{74}Rb and pairing vibrations around ^{56}Ni strongly support its existence.

On the contrary, the observed consequences of the $t = 0$ np -pairing still remain illusive. The existence of the pair condensate in this channel sensitively depends on employed pairing strength. However, microscopic theories give no guidance on what strength has to be used for isoscalar np -pairing in the MF/DFT models. The use of experimental Wigner energies as a tool to extract this strengths faces the dilemma that these energies are not necessary due to isoscalar np -pairing. Other observables in non-rotating nuclei either do not support the existence of this type of pairing or insensitive to it. The systematic analysis of the rotational response of $N \approx Z$ nuclei agrees with the picture which does not involve isoscalar np -pairing. According to it (isovector mean-field theory), at low spin, an isoscalar np -pair field is absent while a strong isovector pair field exists, which includes a large np component, whose strength is determined by isospin conservation. Like in nuclei away from the $N = Z$ line, this isovector pair field is destroyed by rotation. In this high-spin regime, calculations without pairing describe accurately the data, provided that the shape changes and band termination are taken into account. Although the current analysis does not support the existence of isoscalar np -pairing, the possibility of its existence cannot be completely ruled out due to the limitations of existing theoretical tools.

Acknowledgements

This work has been supported by the U.S. Department of Energy under the grant DE-FG02-07ER41459. Useful discussions with S. Frauendorf are greatly appreciated.

References

1. H. H. Wolter, A. Faessler and P. Sauer, HFB calculations with $T = 1$ and $T = 0$ pairing correlations, *Nucl. Phys.* **A 167**, 108-128 (1971).
2. S. Satuła and R. Wyss, Competition between $T = 0$ and $T = 1$ pairing in proton-rich nuclei, *Phys. Lett.* **B 393**, 1-6 (1997).
3. A. Sedrakian and U. Lombardo, Thermodynamics of a n-p condensate in asymmetric nuclear matter, *Phys. Rev. Lett.* **84**, 602-605 (2000).
4. A. L. Goodman, *Adv. Nucl. Phys.* **11**, 263 (1979).
5. D. J. Dean and M. Hjorth-Jensen, Pairing in nuclear systems: from neutron stars to finite nuclei, *Rev. Mod. Phys.* **75**, 607-656 (2003).
6. A. L. Goodman, $T=0$ and $T=1$ pairing in rotational states of the $N = Z$ nucleus ^{80}Zr , *Phys. Rev.* **C 63**, 044325 (2001).
7. A. L. Goodman, G. L. Struble, A. Goswami, Restoration of axial symmetry of the equilibrium shape of ^{24}Mg by pairing correlations, *Phys. Lett.* **B 26**, 257-261 (1968).
8. A. L. Goodman, G. L. Struble, J. Bar-Touv and A. Goswami, Generalized pairing in light nuclei. II: Solution of the Hartree-Fock-Bogoliubov equations with realistic forces and comparison of different Approximations, *Phys. Rev.* **C2**, 380-395 (1970).
9. A. L. Goodman, Proton-neutron pairing in $Z = N$ nuclei with $A = 76 - 96$, *Phys. Rev.* **C60**, 014311 (1999).
10. W. Satuła and R. Wyss, A number projected model with generalized pairing interaction, *Nucl. Phys.* **A 676**, 120-142 (2000).
11. S. G. Frauendorf and J. A. Sheikh, Cranked shell model and isospin symmetry near $N = Z$, *Nucl. Phys.* **A 645**, 509-535 (1999).
12. A. O. Macchiavelli *et al*, Is there np pairing in $N = Z$ nuclei? *Phys. Rev.* **C 61**, 041303(R) (2000).
13. P. Vogel, Pairing and symmetry energy in $N \approx Z$ nuclei, *Nucl. Phys.* **A662**, 148-154, (2000).
14. C. D. O'Leary *et al*, Evidence for isovector neutron-proton pairing from high-spin states in $N = Z$ ^{74}Rb , *Phys. Rev.* **C67**, 021301(R) (2003).
15. D. R. Bes, R. A. Broglia, O. Hansen, O. Nathan, Isovector pairing vibrations, *Phys. Rep.* **34**, 1-53 (1977).
16. A. O. Macchiavelli *et al*, Collective $T = 0$ pairing in $N = Z$ nuclei? Pairing vibrations around ^{56}Ni , *Phys. Lett.* **B480**, 1-6 (2000).
17. A. Macchiavelli, the contribution to this book
18. E. Garrido, P. Sarriguren, E. Moya de Guerra, U. Lombardo, P. Schuck, H.

- J. Schulze, Nuclear pairing in the $T = 0$ channel reexamined, *Phys. Rev. C* **63**, 037304 (2001).
19. M. S. Fayache, L. Zamick, and B. Castel, The nuclear tensor interaction, *Phys. Rep.* **290**, 201 (1997).
 20. D. C. Zheng and L. Zamick, The effects of the spin-orbit and tensor interactions in nuclei, *Ann. Phys. (N.Y.)* **206**, 106 (1991).
 21. E. Garrido, P. Sarriguren, E. Moya de Guerra, and P. Schuck, Effective density-dependent pairing forces in the $T = 1$ and $T = 0$ channels, *Phys. Rev. C* **60**, 064312 (1999).
 22. S. Baroni, A. O. Macchiavelli, and A. Schwenk, Partial-wave contributions to pairing in nuclei, *Phys. Rev. C* **81**, 064308 (2010).
 23. A. Poves and G. Martinez-Pinedo, Pairing and the structure of the pf -shell $N \sim Z$ nuclei, *Phys. Lett. B* **430**, 203-208 (1998).
 24. G. F. Bertsch and Y. Luo, Spin-triplet pairing in large nuclei, *Phys. Rev. C* **81**, 064320 (2010).
 25. W. D. Myers and W. J. Swiatecki, The macroscopic approach to nuclear masses and deformations, *Ann. Rev. Nucl. Part. Sci.* **32**, 309-334 (1982).
 26. K. Neergård, Pairing theory of the symmetry energy, *Phys. Rev. C* **80**, 044313 (2009).
 27. K. Neergård, Interpretation of the Wigner energy as due to RPA correlations, *Phys. Lett. B* **537**, 287-290 (2002).
 28. K. Neergård, On the linear term in the nuclear symmetry energy, *Phys. Lett. B* **572**, 159-163 (2003).
 29. I. Bentley and S. Frauendorf, Wigner energy generated by the isovector pairing, *Phys. Rev. C*, in press, see also nuclear theory archive arXiv:1202.2795v1 (2012).
 30. S. Frauendorf and J. A. Sheikh, Symmetry breaking by proton-neutron pairing, *Phys. Scripta* **T88**, 162-169 (2000).
 31. P. Froöbrich, The effect of neutron-proton pairing correlations on the transfer of a neutron-proton pair, *Z. Phys.* **236**, 153-165 (1970).
 32. P. Froöbrich, Enhancement of deuteron transfer reactions by neutron-proton pairing correlations, *Phys. Lett. B* **37**, 338-340 (1971).
 33. S. Glowacz, W. Satuła and R. A. Wyss, Cranking in isospace, *Eur. Phys. J. A* **19**, 33-44 (2004).
 34. S. Frauendorf and J. A. Sheikh, Rotational alignment near $N = Z$ and proton-neutron correlations. *Phys. Rev. C* **59**, 1400-1404 (1999).
 35. K. Kaneko and J. Zhang, Cranking model with proton-neutron correlations. *Phys. Rev. C* **57**, 1732-1737 (1998).
 36. N. S. Kelsall *et al*, Consequences of neutron-proton pairing correlations for the rotational motion of the $N = Z$ nucleus ^{72}Kr , *Phys. Rev. C* **64**, 024309 (2001).
 37. J. A. Sheikh and R. Wyss, Isovector and isoscalar superfluid phases in rotating nuclei, *Phys. Rev. C* **62**, 051302(R) (2000).
 38. R. A. Wyss and W. Satuła, Rotating $N = Z$ nuclei - a probe to the $t = 0$ and $t = 1$ pairing correlations, *Acta Phys. Pol. B* **32**, 2457-2468 (2001).
 39. Y. Sun, Projected shell model study of nuclei near the $N = Z$ line, *Eur.*

- Phys. J. A* **20**, 133-138 (2004).
40. J. Terasaki, R. Wyss, and P.-H. Heenen, Onset of $T = 0$ pairing and deformations in high spin states of the $N = Z$ nucleus ^{48}Cr , *Phys. Lett. B* **437**, 1-6 (1998).
 41. D. G. Jenkins *et al*, $T = 0$ and $T = 1$ states in the odd-odd $N = Z$ nucleus, $^{70}_{35}\text{Br}_{35}$, *Phys. Rev. C* **65**, 064307 (2002).
 42. N. S. Kelsall *et al*, Testing mean-field models near the $N = Z$ line: γ -ray spectroscopy of the $T_z = 1/2$ nucleus ^{73}Kr , *Phys. Rev. C* **65**, 044331 (2002).
 43. A. V. Afanasjev and S. Frauendorf, Description of rotating $N = Z$ nuclei in terms of isovector pairing, *Phys. Rev. C* **71**, 064318 (2005).
 44. G. Stoitcheva, W. Satuła, W. Nazarewicz, D. J. Dean, M. Zalewski, and H. Zdunićuk, High-spin intruder states in the fp -shell nuclei and isoscalar proton-neutron correlations, *Phys. Rev. C* **73**, 061304(R) (2006).
 45. A. V. Afanasjev, P. Ring, and J. König, Cranked relativistic Hartree-Bogoliubov theory: formalism and application to the superdeformed bands in the $A \sim 190$ region, *Nucl. Phys. A* **676**, 196 (2000).
 46. D. Vretenar, A. V. Afanasjev, G. Lalazissis, and P. Ring, Relativistic Hartree-Bogoliubov theory: static and dynamic aspects of exotic nuclear structure, *Phys. Rep.* **409**, 101-259 (2005).
 47. A. V. Afanasjev, D. B. Fossan, G. J. Lane and I. Ragnarsson, Termination of rotational bands: disappearance of quantum many-body collectivity. *Phys. Rep.* **322**, 1-124 (1999).
 48. C. Andreoiu *et al*, Yrast superdeformed band in ^{59}Cu , *Phys. Rev. C* **62**, 051301(R) (2000).
 49. A. V. Afanasjev, I. Ragnarsson and P. Ring, Comparative study of superdeformed and highly deformed bands in the $A \sim 60$ mass region, *Phys. Rev. C* **59**, 3166-3171 (1999).
 50. C. Andreoiu *et al*, High-spin lifetime measurements in the $N = Z$ nucleus ^{72}Kr , *Phys. Rev. C* **75**, 041301(R) (2007).
 51. F. Johnston-Theasby *et al*, Deformation of rotational structures in ^{73}Kr and ^{74}Rb : Probing the additivity principle at triaxial shapes, *Phys. Rev. C* **78**, 034312 (2008).
 52. J. J. Valiente-Dobón *et al*, Evidence for nontermination of rotational bands in ^{74}Kr , *Phys. Rev. Lett.* **95**, 232501 (2005).
 53. J. J. Valiente-Dobón *et al*, Low-spin lifetime measurements in ^{74}Kr , *Phys. Rev. C* **77**, 024312 (2008).
 54. P. J. Davies *et al*, Evidence of nontermination of collective rotation near the maximum angular momentum in ^{75}Rb , *Phys. Rev. C* **82**, 061303(R) (2010).
 55. D. J. Dean, S. E. Koonin, K. Langanke and P. B. Radha, Rotational and pairing properties of ^{74}Rb , *Phys. Lett. B* **399**, 1-7 (1997).
 56. W. Satuła, J. Dobaczewski, W. Nazarewicz, and M. Rafalski, Isospin-symmetry restoration within the nuclear density functional theory: Formalism and applications, *Phys. Rev. C* **81**, 054310 (2010).
 57. P. J. Davies *et al*, Identification of the $g_{9/2}$ proton and neutron band crossing in the $N = Z$ nucleus ^{76}Sr , *Phys. Rev. C* **75**, 011302(R) (2007).

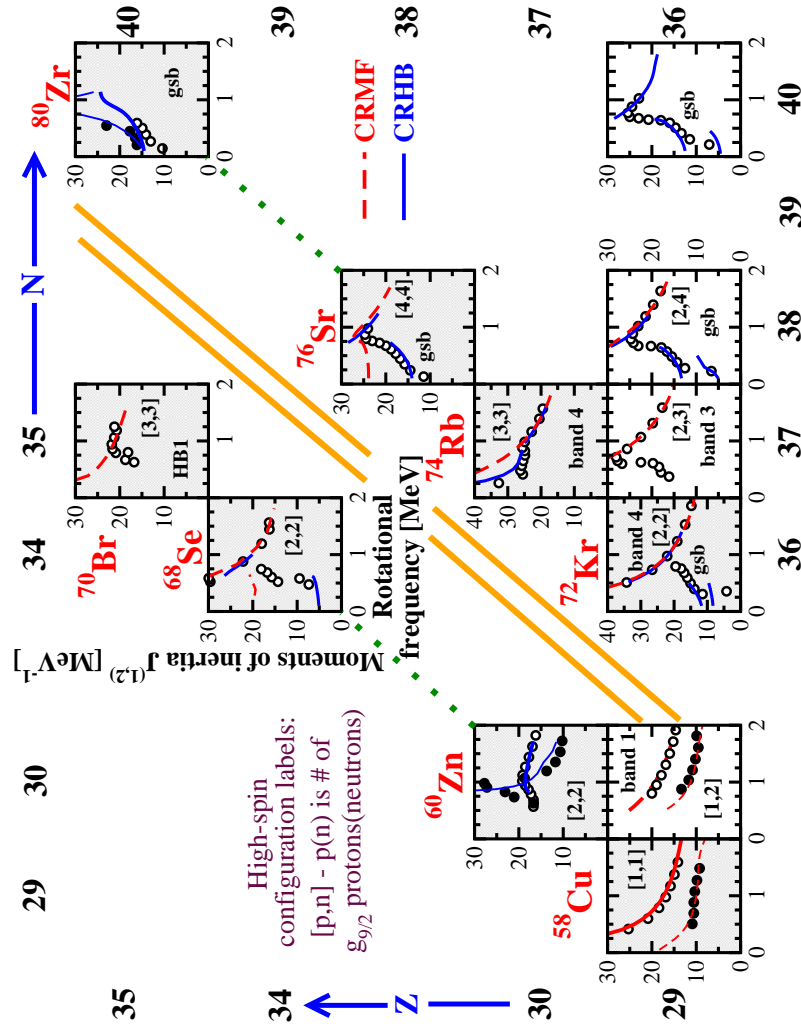


Fig. 3. The kinematic moments of inertia $J^{(1)}$ of rotational structures in the $N \approx Z$ nuclei compared with the results of the CRMF and CRHB calculations. The shaded background is used for $N = Z$ nuclei. The vertical scale of the panels for ^{72}Kr and ^{74}Rb is different from the one of the other panels. The figure is based on the results published in Refs.^{14,41–43,48–50,52,57} Note that in few cases the results for dynamic moments of inertia $J^{(2)}$ are shown. In these cases, thick and thin lines are used for calculated kinematic and dynamic moments of inertia, respectively. Experimental kinematic and dynamic moments of inertia are shown by open and solid circles, respectively. The results of the CRHB calculations at low spin are shown both for prolate and oblate minima in some cases; in a given nucleus calculated $J^{(1)}$ in oblate minimum is lower than the one in prolate minimum.

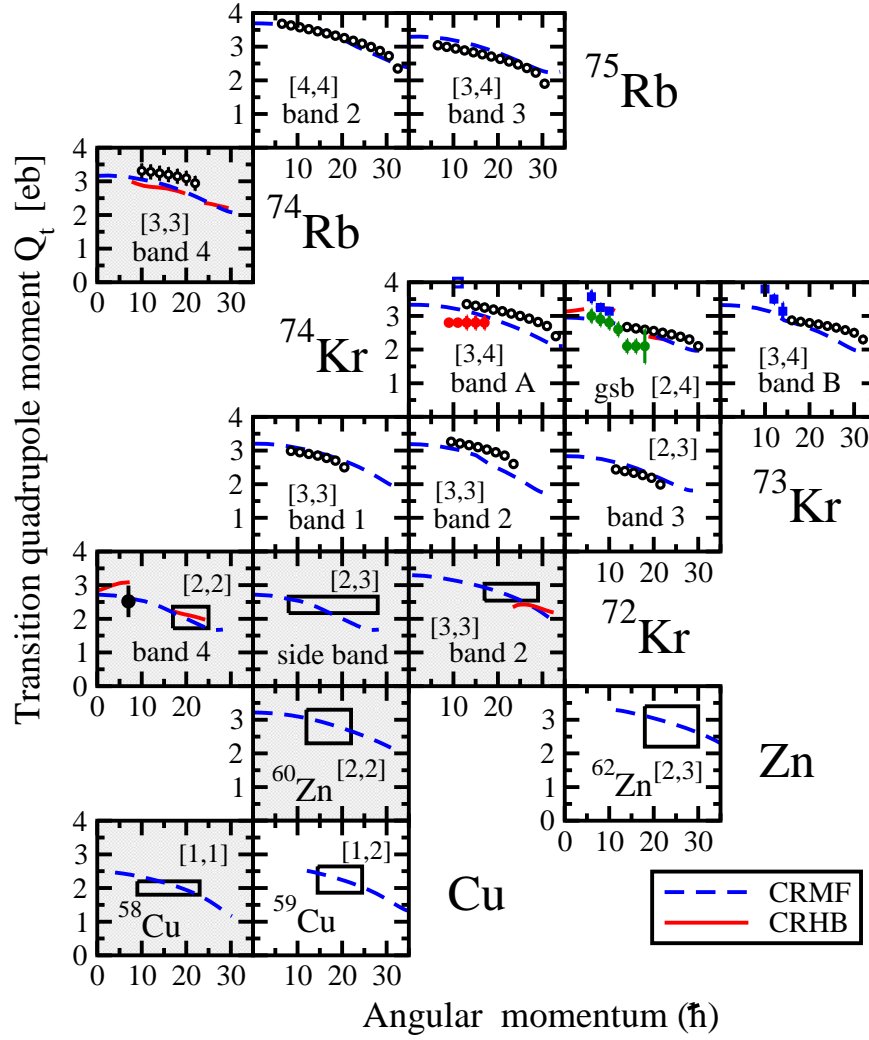


Fig. 4. Transition quadrupole moments as a function of angular momentum. Experimental data are displayed either by data points (when available with most recent ones shown by open circles) or by boxes. The boxes display the measured transition quadrupole moments and their uncertainties within the measured spin range. The results of the CRMF and CRHB calculations are shown. The shaded background is used for $N = Z$ nuclei. Experimental data and the results of calculations are taken from Ref.⁴⁹(^{58}Cu , $^{60,62}\text{Zn}$), Ref.⁴⁸(^{59}Cu), Ref.⁵⁰(^{72}Kr), Ref.⁵¹(^{73}Kr), Refs.^{52,53}(^{74}Kr), Ref.⁵¹(^{74}Rb), and Ref.⁵⁴(^{75}Rb).